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THE DESTRUCTION OF ^{3}He IN STARS

D.P.S. Dearborn
Lawrence Livermore National Laboratory
David N. Schramm
University of Chicago and Fermilab
Gary Steigman
Bartol Research Foundation

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D.S.P. Dearborn

Lawrence Livermore National Laboratory

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ABSTRACT

The observed abundance of ^{3}He can be used, in conjunction with Big Bang Nucleosynthesis, to set a *lower* bound to the density of nucleons in the Universe. Critical to this approach is an estimate of the destruction of ^{3}He in stars. Detailed stellar evolution calculations which explicitly examine ^{3}He destruction are presented. The effect of stellar mass, composition, and mass loss rate on ^{3}He destruction is studied. Limits on ^{3}He destuction appropriate for Big Bang nucleosynthesis and for understanding present interstellar ^{3}He abundances are discussed.

Subject headings: cosmology - nuclear reactions - nucleosynthesis - stars: interiors

Introduction

Knowledge of the production and destruction of ^{3}He in the Galaxy can, in principle, permit the extrapolation of present interstellar and solar system ^{3}He abundances back to primordial epochs. Comparison of such extrapolations with the results of Big Bang Nucleosynthesis yields constraints on the density of baryons in the universe (Yang et al. 1984). The importance of the ^{3}He constraint is enhanced because any cosmological deuterium which is processed in stars will be converted to ^{3}He via radiative proton capture. Since both cosmological D and ^{3}He production increase for lower baryon densities, the sum of the presently observed ^{3}He plus D abundances can be compared with the sum of calculated, primordial abundances to obtain a lower limit on the baryon density *if* some limits can be placed on ^{3}He destruction. Such a lower limit to the baryon density is critical to questions of the existence of dark baryonic matter and the number of cosmologically allowed neutrino flavors. Yang et al. (1984) describe this approach in detail and estimate limits to the ^{3}He destruction, using earlier models of Dearborn et al. (1978). It is the purpose of this paper to reexamine the ^{3}He destruction problem in greater detail, using (complete) stellar evolution models for different mass stars and explicitly examining the dependence on composition and mass loss.

While our prime motivation is the cosmological constraints, ^{3}He evolution is important in its own right (Rood, Steigman and Tinsley, 1976). In particular, it will be important to understand the variations in the interstellar abundance of ^{3}He found by Rood et al. (1984); their estimates range from solar system values (or less) to an order of magnitude higher.

In the next section, ^{3}He production and destruction processes will be discussed as well as the basic stellar evolution models. The following section will then present the results for different mass stars with different chemical compositions and different mass loss rates. In the conclusion we will present limits on ^{3}He destuction averaged over an initial mass function.

Basic Physics

^{3}He is produced by burning of deuterium,

$$D+p\rightarrow{}^3He+\gamma. \tag{1}$$

Since D is weakly bound relative to ^{3}He, and since the reaction has a low Coulomb barrier, the reaction goes rapidly at temperatures of $\gtrsim 6\times10^5$ °K. Since the destruction of ^{3}He via

$$^3He+^3He\rightarrow{}^4He+2p \quad or \quad {}^3He+^4He\rightarrow{}^7Be+\gamma \tag{2}$$

requires surmounting a much higher Coulomb barrier, ^{3}He destruction is not significant until temperatures $\gtrsim 7\times10^6$ °K are achieved. In fact, for temperatures exceeding $\sim10^6$ °K, ^{3}He is being produced via the pp-chain. Any hydrogen burning zone of a star which is not sufficiently hot will produce new ^{3}He, independent of the primordial D and ^{3}He abundances. Low mass, $M\lesssim2M_\odot$, stars are net producers of ^{3}He. For these stars, pp burning is rapid enough to produce D *in situ*, and enable reaction 1 to follow. More massive stars are dominated by CNO burning; although they do produce some ^{3}He via the pp chain in their outer zones, it is not enough to offset the ^{3}He destruction in the interior zones. Iben (1967) and Rood (1972) have shown that the ^{3}He production from such low mass sta... exceeds any primordial ^{3}He present in those stars.

For more massive stars, a large amount of material is processed to temperatures at which any ^{3}He present is burned to ^{4}He or beyond. To estimate ^{3}He destruction, it is the massive stars which are of importance. Therefore, in the following, we concern ourselves with the more massive stars, not the low mass ones which augment any cosmological ^{3}He.

Yang et al. (1984) define a parameter **g** which is the fraction of ^{3}He which survives stellar processing. This parameter **g** depends on the fraction of material processed through massive stars which destroy rather than produce ^{3}He, and on the fraction of that processed material which did not reach temperatures sufficient to destroy ^{3}He. By realizing that massive stars are also producers of non-cosmological ^{4}He (ΔY) as well as the heavy elements (ΔZ) Yang et al. (1984) put limits on **g**($>$ 0.8). However, if the association with nucleosynthesis is relaxed, the lower limit on **g** drops to 0.25 to 0.5, depending on the assumptions. In this work, we reexamine specific massive star models to explore these limits in greater detail. We integrate our results over an initial mass function to relate the ^{3}He survival, $\mathbf{g}_3$, for our individual stellar models, to the net **g**.

For a given mass star, there are two key variables that affect the amount of ^{3}He survival $\mathbf{g}_3$: the amount of mass loss and the composition. Mass loss returns material to the interstellar gas from the star's surface before it has suffered nuclear burning in the interior; the larger the mass loss, the more ^{3}He will survive. We included mass loss as in the stellar models of Dearborn et al. 1978 (hereafter DBHS). The amount of mass loss assumed in those models, was consistent with the observations of Snow and Morton (1976) for O and B stars. Composition affects ^{3}He destruction through changes in the opacities which modify the temperatures and their gradients, thus affecting the boundaries of various nuclear burning zones as well as the temperature within such zones. Since massive stars have stable radiative outer envelopes but convective inner regions, the important question is, how much of the outer radiative zones are at temperatures for which ^{3}He is not destroyed.

The Results

In Table I we summarize the various combinations of composition (Hydrogen, X; Helium, Y; and Heavies, Z) and mass loss for our models. Each model was run for 8, 15, 25, 50 and 100 $M_\odot$. Model 1 is a standard Population I composition (X=0.70, Y=0.28, Z=0.02) without mass loss; Model 4 is a standard Population I composition with mass loss; Models 1a and 2 have Population I composition. These were run to study the effect of Z on the ^{3}He survival. Models 3 and 3a are extreme, low Z (Z=0.0004) models with primordial Y (0.25 and 0.22 respectively). When Models 3 and 3a are compared with Model 2 (X=0.70, Y=0.30, Z=0.0004), we may isolate the effect of Y on the results.

Table II presents the survival fraction, g_3, for each mass and each model. Since the effect of mass loss is negligible for all but the most massive stars, and since such stars contribute minimally to any integration over an initial mass function, mass loss models were only run for one composition model. Notice that even in the most massive case, 100 $M_\odot$, the effect of mass loss was to change g_3 from 0.19 to 0.22, only a 15% effect. Remember that mass loss always goes in the direction of increasing g_3; results obtained without mass loss are good *lower* bounds to g_3.

In fact, stars more massive than $\sim$50 $M_\odot$ will lose mass on a timescale comparable to, or faster than, nuclear burning timescales and, thus, will evolve similiar to $\sim$50 $M_\odot$ stars without mass loss. This is evident by comparing g_3 for 50 $M_\odot$ in Model 1 with g_3 for 100$M_\odot$ in Model 4. Since the mass loss rate is greater for more massive stars, the 50 $M_\odot$ values provide reasonable *lower* limits for g_3. Notice also that, even without mass loss, the most massive stars still have some surviving ^{3}He. The g obtained by integrating over the initial mass function must always be $\gtrsim$0.14 even if the initial mass function were quite different than the Salpeter function. The limit of >0.14 occurs only if very massive stars, $\gtrsim$100$M_\odot$, are produced. This is lower than the 0.2 lower bound of Yang et al. because their estimate was based on calculations similiar to Model 4 but did not include the effect of low Z and low Y.

Note that higher mass stars have more ^{3}He destruction, as anticipated; note also that lower Z yields more ^{3}He destruction. This is because the temperature profile is shifted in such models, and the ^{4}He core grows larger before the star moves on to the other burning stages. This larger ^{4}He core yields more ^{3}He destruction. The later burning stages go so rapidly that they have a negligible effect on ^{3}He destruction. The effect on ^{3}He destruction of decreasing ^{4}He (Y) is slight, as can be seen by comparing models 2, 3 and 3a. There is a very slight increase in ^{3}He survival for lower Y due to a competing combination of the effect of a larger Hydrogen fraction on the opacity and the longer burning time necessary to get [illegible] He core.

In Table III we compare the ratios of g_3 for the different models as functions of stellar mass. We find an intriguing and unanticipated result that *the ratios are (roughly) independent of the stellar mass*; a change in composition causes the same fractional change in ^{3}He survival (for $M \geq 8M_\odot$).

Integration over Mass Function and Conclusions

To estimate the net survival of ^{3}He, **g**, we have integrated over an initial mass function of the Salpeter type

$$\frac{dN}{dM} \approx M^{-\beta}$$

where $\beta > 1$.

Initial mass functions of the Miller-Scalo (1979) variety are steeper for high M and thus even more ^{3}He would survive. The contribution to **g** from stars with $M > 8\ M_\odot$ is

$$<g_3>_8 = [\int_8^{100} f(M)\, dM]^{-1} [\int_8^{15} + \int_{15}^{25} + \int_{25}^{50} + \int_{50}^{100} g_3(M) f(M)\, dM] \tag{3}$$

where

$$f(M) = \frac{M-\mu}{M^{\beta+1}} = \frac{1}{M^\beta} - \frac{\mu}{M^{\beta+1}} \tag{4}$$

where μ is the mass of the remnant star (or black hole).

(Remnant material is not recycled in any further galactic evolution and so does not contribute to the ejected material.)

For $\beta = 1.35$ and $\mu = 1\ M_\odot$ or $1.4\ M_\odot$, we have

$$\int_8^{100} f(M)\, dM = 0.81 = 0.04\mu \tag{5a}$$

$$= 0.77 \text{ for } \mu = 1 M_\odot \tag{5b}$$

$$=0.75 \text{ for } \mu=1.4M_{\odot} \tag{5c}$$

Then, evaluating the integrals, in each of the ranges (I $\equiv$ 8 - 15 $M_{\odot}$, II $\equiv$ 15 - 25$M_{\odot}$, III $\equiv$ 25 - 50$M_{\odot}$ and IV $\equiv$ 50 - 100$M_{\odot}$) we obtain

$$<g_3>_8=0.32g_3^{I}+0.22g_3^{II}+0.20g_3^{III}+0.20g_3^{IV} \tag{6}$$

Table IV shows the results for $<g_3>_8$ for each of the Models of Table I. The $\pm$ values reflect the effect of varying μ from 1 to 1.4 as well as the uncertainties in averaging over the mass ranges $M_i \leq$ M $\leq M_j$ (where either g_3 for M_i, g_3 for M_j or the average could be used). As can be seen from Table IV, the different procedures produce differences of only 10 to 15%.

While in this paper, we have concentrated on ^{3}He survival in the more massive stars (M $>$ 8$M_{\odot}$) where maximal destruction will occur, it is important to estimate the total ^{3}He survival for a generation of stars including the low mass stars. For the mass range 3 to 8$M_{\odot}$ we are in the realm of stars which eventually form degenerate carbon cores and pulsing shell burning zones (Iben 1975). The outer zones of these stars will not destroy ^{3}He and thus an estimate of g_3 for these stars is the fraction of the initial mass which is outside the burning shells. Standard models for these stars yield $g_3 \approx 0.7$ (Iben and Truran, 1978). For these stars, we assume the remnant mass (neutron star or white dwarf) is $\sim$1$M_{\odot}$, so that f(M) = M-1/M$^{2.35}$ for 3 $<$ M $<$ 8. Then, defining $<g_3>_3$ as the integral down to 3$M_{\odot}$,

$$<g_3>_3\equiv[\int_3^8 g_3(M)f(M)dM+<g_3>_8\int_8^{100}f(M)dM] \tag{7}$$

The Third column in Table IV shows the results for $<g_3>_3$ for Models 1, 2 and 3; Model 4 is almost the same as Model 1 and Model 3a is almost identical to Model 3 and 1a is between 1 and 2.

To extend our estimates down to $0.8M_\odot$, we assumed for

$$0.8 < M < 3M_\odot\,, \quad f(M) = \frac{M - 0.7}{M^{2.35}}, \tag{8}$$

where $0.7M_\odot$ is an estimate of the white dwarf remnant mass. Since lower mass stars do not leave the main sequence during the age of the Universe, we do not need to extend our integrals below $0.8M_\odot$. For the range 0.8 to $3M_\odot$, we assumed $g_3 = 1$. We believe this to be a conservative assumption since these stars are actually net producers of ^{3}He. Our estimates for $<g_3>_{0.8}$ should provide lower bounds on the actual survival of ^{3}He.

The results for $<g_3>_{0.8}$ are also shown in Table IV for Models 1, 2 and 3. Note that $<g_3>_{0.8}$ always exceeds 0.5, even for extreme low metal, low He stars; for Pop. I stars, $<g_3>_{0.8}$ exceeds 0.6.

In conclusion, it is clear that even massive stars do not totally destroy their initial ^{3}He (the initial ^{3}He is the sum of the prestellar D plus ^{3}He). From the existence of Deuterium today, as well as the relatively low mass fraction of heavy elements, and the fact that even in Population I, ^{4}He does not greatly exceed primordial values, stellar processing is not complete.

Galactic evolution models in which some material is processed through many stellar generations, are forced to invoke influxes ("infall") of pristine primordial material to dilute Y and Z; such models consequently add D and fresh ^{3}He. Galactic evolution models with variable initial stellar mass functions are constrained from having too much processing through high mass stars by Y and Z and excess ^{3}He from having too much material processed into low mass stars by the paucity of metal poor dwarfs. In fact, as Olive and Schramm (1982) emphasize, processing of all disk material through a single generation with a Salpeter (1955) initial mass function is sufficient to give Pop.I Z. Any, more complex, galactic evolution model must satisfy the same constraints. Thus, from the arguments presented here and as Yang et al. (1984) emphasize, the ^{3}He plus D produced in the Big Bang cannot be destroyed completely. In particuliar, we confirm that the present or presolar its progenitor D.

Yang et al. (1984) show that,

$$\frac{(D+{}^3He)}{H} \leq (2.4+\frac{1.9}{g}) \times 10^{-5}. \tag{9}$$

Thus, for $<g_3>_{0.8}$ >0.5 we obtain

$$\frac{(D+{}^3He)}{H} \leq 6.2 \times 10^{-5} \tag{10}$$

From Big Bang Nucleosynthesis (Yang et al. 1984) this implies a lower limit to the baryon to photon ratio, $n_b/n_\gamma \equiv \eta > 4 \times 10^{-10}$ which in turn implies that the fraction of the critical density in baryons is,

$$\Omega_b > 0.015 h_0^{-2} (T_0/2.7)^3 \tag{11}$$

Where h_0 is the Hubble constant in units of 100 km/sec/Mpc and T_0 is the present temperature of the microwave background.

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Table I Model Parameters				
Model #	X	Y	Z	dM/dt
1	0.70	0.28	0.02	0.0
1a	0.70	0.30	0.004	0.0
2	0.70	0.30	0.0004	0.0
3	0.75	0.25	0.0004	0.0
3a	0.78	0.22	0.0004	0.0
4	0.70	0.28	0.02	DBHS

Table II ^{3}He Survival						
M_s	$g_3^{(1)}$	$g_3^{(1a)}$	$g_3^{(2)}$	$g_3^{(3)}$	$g_3^{(3a)}$	$g_3^{(4)}$
8	0.51	0.41	0.33	0.35	0.37	0.51
15	0.37	0.30	0.23	0.24	0.25	0.37
25	0.30	0.24	0.18	0.19	0.19	0.32
50	0.23	0.19	0.14	0.14	0.15	0.27
100	0.19	0.16	0.11	0.12	0.12	0.22

Table III Comparison of Models					
M_s	$g_3^{(1)}:g_3^{(1a)}$	$g_3^{(1)}:g_3^{(2)}$	$g_3^{(2)}:g_3^{(3)}$	$g_3^{(3)}:g_3^{(3a)}$	$g_3^{(4)}:g_3^{(1)}$
8	1.23	1.25	0.93	0.95	1.00
15	1.24	1.30	0.95	0.97	1.00
25	1.24	1.33	0.96	0.98	1.07
50	1.24	1.35	0.97	0.99	1.14
100	1.20	1.35	0.98	0.99	1.18

Table IV Averages Over a Stellar Generation			
Model #	$<g_3>_8$	$<g_3>_3$	$<g_3>_{0.8}$
1	0.33±0.05	0.47±0.03	0.63±0.02
1a	0.26±0.03		
2	0.20±0.03	0.38±0.02	0.58±0.01
3	0.22±0.03	0.04±0.02	0.54±0.01
3a	0.22±0.03		
4	0.34±0.03		

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